monly used in conjunction with coordinate measuring machines (CMM) to locate mechanical datums.

[0055] Automation of a measurement, alignment or assembly process is possible with integration of a PSM into an automated CMM or other measuring apparatus or machine having coordinated motion. To support automation it is necessary to capture images in a computer from the PSM detector as well as to quantitatively analyze captured images. Quantitative image analysis may be used to determine the distance from optimal focus both longitudinally (focus) and laterally in either standard or interference modes of operation. Additionally, the use of phase shifting techniques in interference mode can further extend the precision of this process. As a result, it is possible to use the PSM as a sensor in a profilometer to measure the surface shape of an object with a sufficiently smooth surface.

[0056] A fully automated CMM or other measuring apparatus is not always appropriate. Yet, even when using a PSM in conjunction with a manual CMM or other measuring apparatus quantitative image analysis can be beneficial. For example a dedicated device may be used to generate a calibrated video marker visible on a video monitor. The calibrated video marker can be used to define a tolerance zone to allow for visual comparison against a predefined tolerance for measurement, alignment or assembly applications.

[0057] Additionally, it is possible to use a lens design program to locate the apparent center of curvature of an optical element (or tooling ball or pin) as viewed through one or more optical elements. This information can be used when assembling multiple element systems to ensure that each component is properly positioned when locating the center of curvature of an element with a PSM through one or more optical elements.

[0058] Additional care is required when performing the assembly and alignment of an optical system involving one or more aspheric elements. Since an aspheric element has a continuous range of radii of curvature, it is often useful to mask an aspheric element so that only a specified portion is viewed, usually the paraxial zone. The size of the mask is set to limit the portion of the aspheric surface used so that the variation of radius of curvature over the exposed portion of the aspheric surface is sufficiently small to produce a good test image in the PSM. If the variation is too large

the point image in the PSM will be larger than desired and limit the accuracy of any measurements. Masking an aspheric surface removes the ambiguity that results from the range of radii of curvature that would otherwise exist.

[0059] Through use of the PSM, additional benefits have become apparent. The source of these benefits is that a PSM, though using a two-dimensional detector, actually provides information about not only the two lateral coordinates, but also the third coordinate – axial distance. This is because alignment of the PSM to a spherical surface requires correct lateral positioning as well as focus for the axial coordinate, while a CMM with a touch probe only obtains two coordinates per measurement. In practice, a touch probe requires at least four measurements to determine accurately the x-y-z position of a tooling ball, while the PSM obtains simultaneously all three coordinates in one measurement. With recognition of the inherent ability of a PSM to locate all three coordinates in a single measurement, suitable CMM software would permit many measurement applications to be performed using a non-contact probe (the PSM) much more quickly than with a touch probe. One especially useful technique when using a PSM on a CMM is to set the probe-tip radius as zero or effectively zero. As a result, when the PSM is aligned to the center of a tooling ball and a measurement is taken on the CMM with a zero radius probe tip, the center of the tooling ball is measured directly without any offset.

[0060] A practical source for a PSM for general use is a fiber-coupled laser diode with an adjustable power level. Higher power settings make it possible to see the PSM illumination directly when scattered or reflected by a surface. This makes it easy to locate the PSM projected spot and to rapidly align the PSM. Switching to lower power may be necessary to avoid saturating the detector. A variable power light source is not necessary in automated applications where the PSM is automatically brought to a nominal position; however, in a manual environment it is frequently helpful.

[0061] One of the applications that can make use of the PSM on a CMM is in measuring the location of holes in a plate. The plate can even have varying heights, provided the CMM has sufficient vertical motion. The basic requirement is to set a tooling ball in each hole to be measured. Tooling balls are usually mounted on a stud

and the stud place in the hole; however, a bare tooling ball may be used. This does add an operation; however, now a single measurement of the tooling ball is required rather than several touches with a touch probe at each hole.

[0062] The height of a plane and its tilt can be measured by placing a tooling pin or plug gauge upon the plate. The PSM will now have a line focus rather than a point focus. The height of the tooling pin can be easily measured as well as tilt of the surface by measuring the tilt of the line focus. Additionally, a pin can be placed in a hole and the center and orientation of the hole can thereby be measured.

[0063] The PSM is much more convenient than a touch probe when establishing a full, local coordinate system of a part on a CMM. When determining a plane defined by three tooling balls using a touch probe, it is necessary to measure each ball twice: first measuring all three balls to determine the height of the plane, then measuring two of the balls to determine the rotation of the plane about a vertical axis, and then measuring the remaining ball to define the origin in the x-y plane. Additionally, the measurement of the center of each ball requires several touches of a probe. The same operation with a PSM can be performed by a single measurement that yields the three orthogonal spatial coordinates of the center of each of the three balls.

[0064] Accessory lenses can be installed on a PSM to better match specific applications. For example, the testing of a convex surface requires a working distance that is larger than the radii of curvature of the surface being measured. Also, some optical components have a large numerical aperture and need the PSM to match their numerical aperture (NA). Furthermore, an accessory lens that produces a collimated output is very useful since it permits the measurement or comparison of angles, e.g., the direction of the normal of a flat or nearly flat surface.

[0065] Fundamental to the operation of the PSM is the use of a point source 20 and the PSM is therefore an ideal source in a Star Test. This makes the PSM useful for measurement of the quality of optical components or systems as well, not just for locating optical or mechanical datums.